Observing with Sibling and Twin Telescopes

Lucia Plank[1], Jim Lovell[1], Jamie McCallum[1], David Mayer[2]

Abstract With the transition to VGOS, co-located radio telescopes will be common at many sites. This can be as a sibling telescope when a VGOS antenna is built next to a legacy one, or as the concept of a twin telescope with two identical VGOS antennas. The co-location of two antennas offers new possibilities in both operation and analysis. The immediate question for observing with sibling/twin telescopes is the applied observing strategy and its realization in the scheduling software. In this contribution we report about our efforts implementing new scheduling modes for sibling and twin telescopes in the Vienna VLBI Software. For the example of the sibling telescope in Hobart, several types of sessions will be discussed: an improved tag-along mode for the 26-m antenna (Ho), a proper implementation of the twin-mode using the antenna with the shorter slewing time, and an astrometric support mode enabling the observation of weak sources with the AuScope array.

Keywords Scheduling, twin telescopes, sibling telescopes

1 Introduction

The idea of the VLBI Global Observing System (VGOS, e.g., Petrachenko et al., 2009) initiated a global infrastructure upgrade effort, with many new telescopes completed or being built worldwide. In general, the new telescopes are smaller (∼12–15 m) and slew faster (up to 12°/s in azimuth) than traditional antennas used for geodesy. Often these new antennas are co-located with existing, legacy antennas. Until the VGOS broadband system is widely adopted, there will be a period of common compatibility in terms of frequency and mode of operation.

Currently, there are co-located antennas in Hobart (Hb-12m, Ho-26m), HartRAO (Ht-15m, Hh-26m), Yebes (Yj-13m, Ys-40m), and Wettzell (Wn-13m, Wz-20m) which have participated in common observations in legacy S/X-mode. Others are on their way (e.g., Ny-Ålesund, Kokee) and often plan an overlapping period. This is important for establishing a local tie realized by VLBI measurements, complimentary to local surveys. In the following, we call such co-located telescopes of different capabilities *sibling telescopes* (Figure 1, left).

Alternatively, the VGOS concept also includes so-called *twin telescopes* (Figure 1, right). These are two co-located antennas of identical capabilities, as realized in the future in Wettzell, Ny-Ålesund, and Onsala.

Fig. 1 Terminology of a sibling telescope with different attributes in sensitivity and slew speeds and a twin telescope with identical capabilities.

1. University of Tasmania
2. Technische Universität Wien

Common operation of co-located telescopes requires new ideas in observing as well as in analysis. In this contribution we concentrate on the immediate question of the scheduling, meaning the planning of common experiments. Using the scheduling module of the Vienna VLBI software (Böhm et al., 2012; Sun, 2013; Sun et al., 2014), we report on new implementations for scheduling the sibling telescopes in Hobart.

2 Scheduling within the AUSTRAL Network

Our testbed is the AUSTRAL network shown in Figure 2. This comprises the AuScope VLBI array (Lovell et al., 2013) with the 12-m telescopes in Hobart (Hb), Katherine (Ke), and Yarragadee (Yg); the antenna in Warkworth (Ww) having the same design as the AuScope dishes; and the 15-m telescope in Hartebeesthoek (Ht). In addition, there are two 26-m legacy antennas in Hobart (Ho) and Hartebeesthoek (Hh).

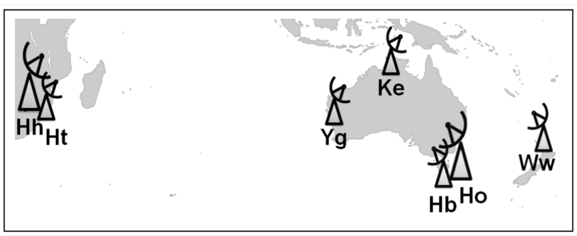

Fig. 2 Antennas in the AUSTRAL network.

Before discussing several new scheduling modes, it is important to understand the basic theory of scheduling. For a deeper understanding the interested reader is referred to scheduling-specific literature such as Gipson (2016) or Sun (2013).

In the schedule, one has to decide which antennas will observe which source and when. As a basic scheduling strategy one can say that the more scans (two or more antennas observing the same source) the better, a second optimization criteria would be *sky coverage*, based on the assumption that scans at different elevation and azimuth help to better resolve the tropospheric errors. Based on a given target SNR (signal-to-noise ratio) of usually 15 or 20, the scan length t_{scan} is determined based on the strength of the source (source flux), the sensitivities of the contributing antennas (measured in antenna specific *system equivalent flux density (SEFD)*), and the data rate as a measure how much data is recorded per time unit:

$$t_{scan} \approx \left(\frac{\text{SNR}}{\text{flux}}\right)^2 \cdot \frac{SEFD_1 \cdot SEFD_2}{\text{data rate}} \tag{1}$$

The scan length has to be determined for each baseline, meaning each antenna pair in the network of antennas observing the same source. It is the weakest partner antenna that determines how long a telescope has to stay on source.

In between scans, the slewing time an antenna needs to move from one source to the next has to be calculated. In general one can say that the old, typically larger, legacy antennas are more sensitive but slower, while the new small dishes are less sensitive but can slew much faster. Also, weaker sources have to be observed longer than strong ones. To overcome the longer on-source times, the VGOS concept includes the transition to a much higher data rate of up to 32 Gbps, compared to 256 Mbps that is commonly used today. In the AUSTRAL network we usually perform AUSTRAL experiments (Plank et al., 2015) with a 1-Gbps data rate.

While scheduling telescopes of a similar type is rather simple, it becomes more complicated when different types of antennas are used. It then has to be decided, for example, whether one should wait for a slow antenna and accept idle time for the fast telescopes or skip the slow antenna in a scan and allow more observations for the fast antennas. Additional complications arise when multiple sub-nets are observing at the same time. In this work we concentrate on the AUSTRAL network without the African antennas where there is almost no sub-netting necessary.

2.1 New Tag-along Mode

In the first example we have the four 12-m telescopes in Australia/New Zealand and intend to add the 26-m Ho antenna. In order to distinguish between different scheduling options, we give the number of scans per hour for each station in Table 1. For improved schedules, we aim for a high number there.

When only scheduling the four fast 12-m antennas (HbKeYgWw), we find 37 scans per hour per station. When we add the 26 m to the network, this number reduces to 24 scans for the 12-m stations and to 23 scans for Ho, respectively. Without special measures, Vie_sched favors larger networks causing the fast antennas to wait for Ho. This leads to about 45% idle time for the 12-m dishes.

Table 1 Number of scans per hour for each antenna of the Australian/New Zealand network plus the 26-m Ho antenna. The new mode is the improved tag-along mode.

# of scans/h	fast 12-m	Ho
HbKeWwYg	37	–
+ Ho	24 (45% idle)	23
+ Ho new mode	37	16

The classical way to include a telescope in a schedule without *disturbing* it is the so-called tag-along mode. For this, the schedule is first created without this additional antenna. In the end the software goes through the schedule and looks for scans that the new antenna can reach in time and which are long enough to get sufficient SNR on all baselines. For our schedule we chose a slightly different approach: we simply decided not to wait for Ho when determining the start time of a scan and Ho can take part whenever it can reach the source in time. The advantage over the classical tag-along mode is the fact that our strategy includes Ho in all other optimization criteria such as the sky-coverage or higher weight for scans with more antennas. Applying this new *improved tag-along mode* we find that Ho does not weaken our schedule. We keep the 37 scans/h for the small dishes and get a decent 16 scans/h for Ho.

This new mode allows us to schedule the Ho antenna in the AUSTRAL network without influencing the number of scans for the small antennas. Hence we expect to keep the high precision in geodetic results (e.g., baseline lengths) and additionally get local baseline observations for the determination of the local tie. However, a thorough comparison with the standard tag-along mode or in terms of sky coverage has not been done so far.

2.2 Twin Mode

The second newly implemented scheduling mode is the proper scheduling of twin telescopes. Before going into detail on this, let us recall the main reasons for the twin concept:

- the main idea is to get more observations at one site. While one antenna is observing, the other can already slew to the next source;
- a second motivation is to overcome maintenance without disturbing continuous observations;
- a third interesting mode is simultaneous observations of different sources. This would allow for a better scanning of the troposphere, the largest error source in VLBI today.

For the implementation of the twin mode we chose that only one dish of the twin is observing while the other has time for slewing. For a scan, the software picks whichever antenna has the shorter slewing to come on source. In our example schedule, we chose the Hobart *twin* in the AuScope network. To simulate a twin telescope, both antennas were given the sensitivity and *fast* slew speeds of the Hb antenna (5°/s in azimuth and 1.25°/s in elevation).

We find that in the AuScope network with three identical antennas, a twin is not much use. Whether Hb is scheduled as a twin or as single dish, we find 49 scans/h (Table 2).

Table 2 Number of scans per hour for different schedules, illustrating that a *fast* twin telescope can overcome its shortcomings in a network of *very fast* antennas.

# of scans/h	AuScope
3 slow	49
3 fast	58
2 fast + Hb	51
2 fast + Hb + Ho	58

We then simulated three *very fast* antennas (12°/s in azimuth and 6°/s in elevation) in 1-Gbps AUSTRAL mode, which would give us 58 scans/h.

When we further assume that only Ke and Yg are *very fast* while Hb keeps its real speed, the number of scans per hour drops to 51. If finally Hobart is replaced with a *fast* twin telescope, this can compensate for the reduced slew speed and we find again 58 scans per station (counting Hb and Ho as one station).

This means, that in a network of *very fast* VGOS telescopes a twin telescope with reduced slew speeds can keep up with the high cadence source switching.

2.3 Star Mode

The final new mode is the so-called star mode. The motivation for it was enabling the AUSTRAL network with its small and low-sensitivity antennas to carry out experiments with astrometric demands. The idea is to add the Ho antenna to the network and increase the network's sensitivity allowing for observations of weaker sources.

However, while adding the Ho antenna would give higher sensitivity on baselines with this large antenna, it would not change anything on the other baselines, e.g., between Yg and Ke. As a consequence, the total length of the scan in the whole network will not change, neither would it become possible to observe weaker sources. With the AuScope array, sources down to 0.4 Jy flux can be observed with scan lengths of up to 500 seconds.

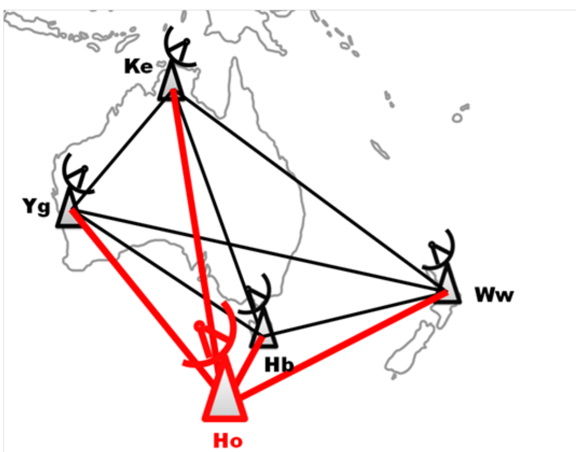

Fig. 3 Illustration of the star mode. The scan length is determined only using the baselines including Ho (thick red lines).

In order to fully exploit the contribution of an additional, more sensitive antenna, we developed the star mode as illustrated in Figure 3. In cases of weak sources, the scan length is determined only using the baselines to Ho. It is then most likely that on the other baselines between two small antennas only an insufficient SNR will be achieved leading to non-detections on these observations. On the other hand, it allows the observation of much weaker sources. In the case of the AuScope array plus Ho, keeping the scan lengths under ten minutes allows sources down to about 0.15 in X-band and 0.2 in S-band to be observed.

It is then the task of the scheduling software to properly mix *normal* scans for the whole network and those to *special sources* in the star mode.

We have realized this new mode for the session AUA009 observed on February 23, 2016. Participating antennas were the 12-m antennas Hb, Ke, Yg, and Ww plus the 26-m antenna Ho. In addition we selected a list of seven weak sources (Table 3).

Table 3 List of target *special* sources for AUA009 including their flux in X- and S-band.

source	X-flux	S-flux
0244–470	0.40	0.25
0212–620	0.40	0.30
0758–737	0.15	0.20
0918–534	0.16	0.50
1334–649	0.20	0.20
1941–554	0.20	0.20
2333–528	0.40	1.00

Without modification in the scheduling, these target sources would be observed with scan lengths of up to 60 minutes or more, which is not very practicable. When applying the new mode, these lengths were reduced to reasonable one–ten minute scans.

Practically we realized a combination of classical geodetic scans with the 12-m antennas to strong sources with Ho in tag-along. Every thirteenth scan was scheduled to one of the target sources applying the star mode. This gives about ten scans for each of these target sources over the 24-hour session. While the parameter for balancing between standard and target scans (13:1) was determined iteratively, all other scheduling is fully automated.

For AUA009, we find 34 scans/h for the 12-m antennas and 12 scans/h for Ho (Table 4).

Table 4 Overview of scan numbers in AUA009 for the 12-m antennas, the large Ho antenna, and for the special target sources.

# of scans/h	12-m	Ho	special sources
AUA009	34/h	12/h	∼10/24h

Small shortcomings of this mode at the moment are that for Ho the *old* tag-along mode (see Section 2.1) is used without considering Ho for the sky coverage. Also, as already mentioned above, it is only semi-automated so far.

3 Summary and Outlook

For the example of the sibling telescope in Hobart and its application in AUSTRAL sessions we have developed three new scheduling modes, all implemented in a preliminary version of Vie_sched.

The new tag-along mode allows for local baseline measurements between the new and the legacy telescopes, without degrading the schedule for the small and fast dishes. The star mode is an innovative schedule with the new concept of determining the scan lengths for only a sub-set of baselines within a network. This new strategy is very promising and was already applied in AUA009 (with correlation under way at the moment). This new mode allows the AuScope array to undertake much more responsibilities in monitoring sources in the southern sky, as by addition of one or more large telescopes the sensitivity can be significantly increased.

Future developments of these new modes will include refinements in the software implementation, application to real sessions, as well as investigations concerning the extension to larger networks comprising several sibling and twin telescopes.

Acknowledgements

This work was supported by the Austrian Science Fund (FWF, projects J 3699-N29 and I 2204) and the AuScope Initiative, funded under the National Collaborative Research Infrastructure Strategy (NCRIS), an Australian Commonwealth Government Programme.

References

Böhm J, Böhm S, Nilsson T, Pany A, Plank L, Spicakova H, Teke K, Schuh H (2012) The new Vienna VLBI Software VieVS. In: Proceedings of the 2009 IAG Symposium, Buenos Aires, Argentina, International Association of Geodesy Symposia, vol 136, doi: doi:10.1007/978-3-642-20338-1_126.

Gipson J (2016) SKED VLBI Scheduling Software. Goddard Space Flight Center ftp://gemini.gsfc.nasa.gov/pub/sked/SkedManual_v2016Jan31.pdf.

Lovell J, McCallum J, Reid P, McCulloch P, Baynes B, Dickey J, Shabala S, Watson C, Titov O, Ruddick R, Twilley R, Reynolds C, Tingay S, Shield P, Adada R, Ellingsen S, Morgan J, Bignall H (2013) The AuScope geodetic VLBI array. J Geod 87:527–538

Petrachenko B et al. (2009) Progress Report of the IVS VLBI2010 Committee: Design Aspects of the VLBI2010 System. NASA/TM-2009-214180 ftp://ivscc.gsfc.nasa.gov/pub/misc/V2C/TM-2009-214180.pdf.

Plank L, Lovell JE, McCallum J, Rastorgueva-Foi E, Shabala SS, Böhm J, Mayer D, Sun J, Titov O, Weston S, Gulyaev S, Natusch T, Quick J (2015) Results from the regional austral VLBI sessions for southern hemisphere reference frames. International Association of Geodesy Symposia, Springer Berlin Heidelberg, pp 1–6, doi: doi:10.1007/1345_2015_132.

Sun J (2013) VLBI scheduling strategies with respect to VLBI2010. Geowissenschaftliche Mitteilungen 92, Schriftenreihe der Studienrichtung Vermessung und Geoinformation, Technische Universität Wien, ISSN 1811-8380.

Sun J, Böhm J, Nilsson T, Krásná H, Böhm S, Schuh H (2014) New VLBI2010 scheduling strategies and implications on the terrestrial reference frames. J Geod 88:449–461.